

1 **Improved Mode Selection and Frequency Tuning of a Laser**  
2 **Cavity**

3

4 The present invention relates to a method and apparatus  
5 for improving the mode selection and frequency tuning of  
6 a laser cavity. In particular, the invention relates to  
7 the incorporation of an intracavity, anisotropic etalon  
8 that provides a means for selecting and stabilising the  
9 laser cavity to a single mode operating frequency.

10

11 The use of single frequency lasers relies heavily on the  
12 ability to select a mode of the laser cavity and maintain  
13 it for an extended period of time. This may also include  
14 tracking the mode if the length of laser cavity is  
15 scanned in order to change the output frequency. This  
16 selection is normally carried out with a combination of  
17 optical elements inserted into the cavity. These  
18 elements may include birefringent filters and etalons.

19

20 In the case of widely tuneable lasers the frequency  
21 selection requirements placed on these elements are  
22 particularly stringent. The first requirement results  
23 from the fact that the desired mode of operation is one

1 of a great number of possible modes on which the cavity  
2 may operate. Secondly, the need to tune the laser  
3 frequency implies that the selecting element has to be  
4 tuned as well, typically by being rotated around one of  
5 its axes. As a result, the non-solid mounting techniques  
6 normally employed for the selecting element to be rotated  
7 makes the laser frequency prone to drifting.

8

9 Two main classes of widely tuneable single frequency  
10 lasers known to those skilled in the art are Dye lasers  
11 and Ti:Sapphire lasers. In both cases the tuning range  
12 provided by the gain medium is in excess of 50 THz (or  
13 more than 100 nm). The laser cavity modes of which a  
14 single one has to be selected are typically spaced by a  
15 few hundred MHz. Selection is achieved by insertion  
16 within the cavity of a number of optical elements, each  
17 of which introduces an operating power loss that is a  
18 periodic function of the laser frequency. This period is  
19 referred to as the free spectral range (FSR) of the  
20 element. Typically, the elements chosen to achieve  
21 single frequency operation are selected to have  
22 successively smaller free spectral ranges corresponding  
23 to successively narrower regions of low insertion loss.  
24 As a result only one laser mode is capable of oscillating  
25 at a frequency corresponding to a loss minimum of all of  
26 the inserted elements. The exact requirements for the  
27 mode selecting elements are known to depend on the amount  
28 of inhomogeneous to homogeneous broadening in the gain  
29 medium as well as any spatial hole burning effects.

30

31 In a tuneable single frequency laser coarse wavelength  
32 selection is typically achieved through the employment of  
33 a birefringent filter within the cavity. This may

1 consist of one or more plates made of a birefringent  
2 material and is rotated to select a laser bandwidth of  
3 typically less than 200 GHz (0.5 nm). At this point it  
4 is often sufficient just to insert a fused silica etalon  
5 with a free spectral range of approximately 200 GHz into  
6 the cavity to ensure single-mode operation. However, the  
7 stability requirements are extremely stringent as the  
8 rotation of the etalon by an angle of an order of one  
9 thousandth of a degree is sufficient for the laser to  
10 jump to the next mode of operation.

11

12 Two main methods have been employed by those skilled in  
13 the art in order to prevent the detrimental effect of  
14 mode jumping:

15

16 1) The first method comprises a passive stabilisation  
17 technique that involves the addition of a second  
18 etalon, with an even smaller free spectral range,  
19 thereby reducing the sensitivity of the first  
20 etalon. In the case of a widely tuneable laser an  
21 appropriate feed-forward has to be applied to this  
22 second etalon in order to track the scanning laser  
23 mode. This technique has been successfully  
24 implemented within the commercially available  
25 Coherent 599/699/899 series of Dye lasers.

26

27 2) The second method comprises an active stabilisation  
28 technique whereby a feedback is applied to the  
29 rotation of a solid etalon so as to keep it locked  
30 to the laser mode over long periods of time, and  
31 also while the laser is being scanned. This  
32 technique is employed within the commercially  
33 available Coherent MBR 110 Ti:Sapphire laser 1, see

Figure 1. In particular the electronic signal required for the stabilisation is derived by modulating the angle of the solid etalon 2 at a frequency of 80-90 kHz around a reflection minimum.

Generally, it is appreciated that the fewer intracavity elements included within a laser cavity the simpler the system is to operate, as there are fewer difficulties in relation to the optical alignment of the cavity. Furthermore, the incorporation of additional elements within the laser cavity also acts to reduce the overall output power of the system as each intracavity element introduces an inherent power loss. Therefore, employing the above passive technique has particular disadvantages over that of the described active technique.

Modulating the solid etalon 2 angle so as to derive an error signal for locking the solid etalon 2 to the cavity in the above active stabilisation technique produces certain inherent detrimental effects on the operation of the laser. In the first instance, the modulated solid etalon 2 introduces a loss in the cavity at twice the modulation frequency, and hence an undesirable intensity modulation results. Secondly, the etalon 2 sets up acoustic vibrations in the cavity, which are then required to be compensated for through the employment of complex electronics.

It is an object of aspects of the present invention to provide a method and apparatus for improving the mode selection and frequency tuning of a laser cavity so as to overcome one or more of the limiting features associated

1 with the methods and apparatus described in the prior  
2 art.

3

4 According to a first aspect of the present invention  
5 there is provided a frequency stabilisation apparatus for  
6 stabilising a frequency output of a laser cavity, the  
7 frequency stabilisation apparatus comprising an  
8 intracavity birefringent etalon, wherein the intracavity  
9 birefringent etalon is employed to derive a polarised  
10 electric field component from an intracavity electric  
11 field of the laser cavity, the orientation of  
12 polarisation of the polarised electric field component  
13 being dependent on the frequency and polarisation of the  
14 intracavity electric field.

15

16 Most preferably the intracavity birefringent etalon acts  
17 as a first quarter waveplate on the polarised electric  
18 field component such that when the frequency of the  
19 intracavity electric field corresponds to a resonant  
20 frequency of the birefringent etalon the polarised  
21 electric field component is linearly polarised.

22

23 Preferably the frequency stabilisation apparatus further  
24 comprises a second quarter waveplate.

25

26 Preferably the frequency stabilisation apparatus further  
27 comprises an elliptical polarisation analyser for  
28 analysing the state of polarisation of the polarised  
29 electric field component on being transmitted through the  
30 second quarter waveplate.

31

32 Optionally an optical axis of the second quarter  
33 waveplate is aligned with an optical axis of the

1 birefringent etalon such that on being transmitted  
2 through the second quarter waveplate the polarised  
3 electric field component is linearly polarised, the plane  
4 of linear polarisation being dependent on the frequency  
5 of the intracavity electric field relative to the  
6 resonant frequency of the birefringent etalon.

7

8 In an alternative arrangement an optical axis of the  
9 second quarter waveplate is aligned at 45° relative to an  
10 optical axis of the birefringent etalon such that on  
11 being transmitted through the second quarter waveplate  
12 the polarised electric field component of an off  
13 resonance frequency is linearly polarised, the plane of  
14 linear polarisation being dependent on the frequency of  
15 the intracavity electric field relative to the resonant  
16 frequency of the birefringent etalon.

17

18 Optionally the elliptical polarisation analyser comprises  
19 a polarisation dependent beamsplitter and two light  
20 detecting means wherein the polarisation dependent  
21 beamsplitter is orientated so as to resolve the polarised  
22 electric field component into two spatially separated  
23 components each of which is incident on one of the light  
24 detecting means.

25

26 Preferably the elliptical polarisation analyser further  
27 comprises an electronic circuit wherein the electronic  
28 circuit derives an error signal from electrical output  
29 signals generated by the two light detecting means.

30

31 Preferably the electronic circuit further comprises a  
32 feedback circuit for generating a feedback signal in  
33 response to the error signal so as to control the

1 orientation of the birefringent etalon within the  
2 intracavity electric field in order to minimise the  
3 magnitude of the error signal.

4

5 According to a second aspect of the present invention  
6 there is provided frequency scanning apparatus for  
7 scanning a frequency output of a laser cavity comprising  
8 frequency stabilising apparatus in accordance with a  
9 first aspect of the present invention and a cavity length  
10 adjuster that provides a means for scanning a length of  
11 the laser cavity.

12

13 Preferably the cavity length adjuster comprises at least  
14 one laser cavity mirror mounted on a piezoelectric  
15 crystal.

16

17 According to a third aspect of the present invention  
18 there is provided a method for stabilising a frequency  
19 output of a laser cavity comprising the steps of:

20 1) Employing a birefringent etalon to sample an  
21 intracavity electric field of the laser cavity so as to  
22 derive a polarised electric field component whose  
23 polarisation is dependent on the polarisation and  
24 frequency of the intracavity electric field relative to  
25 a resonant frequency of the birefringent etalon;

26 2) Deriving an error signal from the polarised field  
27 component; and

28 3) Stabilising the birefringent etalon to the derived  
29 error signal.

30

31 Most preferably the polarised electric field component is  
32 linearly polarised when the intracavity electric field

1 corresponds to a resonant frequency of the birefringent  
2 etalon.

3

4 Preferably the polarised electric field component is  
5 elliptically polarised when the intracavity electric  
6 field corresponds to a non-resonant frequency of the  
7 birefringent etalon. In particular, the helicity of the  
8 polarised electric field component is of an alternative  
9 sign when the intracavity electric field frequency is  
10 above or below the resonant frequency of the birefringent  
11 etalon.

12

13 Preferably the derivation of the error signal comprises  
14 the steps of:

- 15 1) Introducing a  $\pi/2$  phase shift to the orthogonal  
16 constituent components of the polarised electric field  
17 component;  
18 2) Resolving the orthogonal constituent components of the  
19 polarised electric field component; and  
20 3) Calculating an intensity ratio signal the orthogonal  
21 constituent components of the polarised electric field  
22 component.

23

24 Optionally introducing the  $\pi/2$  phase shift to the  
25 orthogonal constituent components of the polarised  
26 electric field component results in the plane of  
27 polarisation of the polarised electric field component  
28 being directly dependent on the frequency of the  
29 intracavity electric field relative to the resonant  
30 frequency of the birefringent etalon.

31

32 Preferably the birefringent etalon is stabilised to the  
33 derived error signal by controlling the orientation of



1 the birefringent etalon within the intracavity electric  
2 field in order to minimise the magnitude of the error  
3 signal

4  
5 According to a fourth aspect of the present invention  
6 there is provided a method for scanning a frequency  
7 output of a laser cavity comprising:

8 1) Stabilising the frequency output of the laser  
9 cavity in accordance with a third aspect of the  
10 present invention;

11 2) Scanning an optical length of the laser cavity;  
12 and

13 3) Scanning the orientation of the birefringent  
14 etalon within the intracavity electric field in  
15 order to track the scanned optical length of the  
16 laser cavity.

17  
18 Aspects and advantages of the present invention will  
19 become apparent upon reading the following detailed  
20 description and upon reference to the following drawings  
21 in which:

22  
23 Figure 1 presents a schematic representation of a  
24 commercially available Coherent MBR 110  
25 Ti:Sapphire laser that incorporates an active  
26 stabilisation technique, as known to those  
27 skilled in the art;

28  
29 Figure 2 presents a schematic representation of  
30 stabilisation apparatus employed within a  
31 vertical external cavity surface emitting laser  
32 (VECSEL), in accordance an aspect of the  
33 present invention;

1

2 Figure 3 presents a schematic representation of the  
3 principle of operation of the stabilisation  
4 apparatus of Figure 2 when employed within an  
5 extra-cavity configuration;

6

7 Figure 4 presents both theoretical and experimental  
8 curves relating to a normalised ratio signal as  
9 a function of input laser frequency, for the  
10 stabilisation apparatus of Figure 3 when  
11 employed with an uncoated birefringent etalon;

12

13 Figure 5 presents an experimental curve of the  
14 normalised ratio signal as a function of  
15 birefringent etalon tuning, for the VECSEL 3 of  
16 Figure 2;

17

18 Figure 6 presents theoretical curves relating to the  
19 normalised ratio signal, as a function of input  
20 laser frequency, for the stabilisation  
21 apparatus of Figure 3 when employed with a 4%,  
22 8%, 12%, 16% and 20% reflecting birefringent  
23 etalon; and

24

25 Figure 7 presents theoretical curves relating to the  
26 normalised ratio signal, as a function of input  
27 laser frequency, for the stabilisation  
28 apparatus of Figure 3 when employed with a 20%  
29 reflecting birefringent etalon and where the  
30 retardation of the birefringent etalon varies  
31 from a value of  $\lambda/8$  to  $3\lambda/8$ .

32

1 Referring to Figure 2 a schematic representation a  
2 Vertical External Cavity Surface Emitting Laser (VECSEL)  
3 3 is presented that incorporates stabilisation apparatus  
4 4, in accordance with an aspect of the present invention.

5  
6 The VECSEL 3 can be seen to comprise a wafer structure 5  
7 mounted within a cooling apparatus 6 that is located  
8 within a three mirror folded cavity arrangement. The  
9 wafer structure comprises a gain medium (not explicitly  
10 shown) made up of twelve 6 nm thick  $\text{In}_{0.16}\text{GaAs}$  quantum  
11 wells equally spaced between half-wave  $\text{Al}_{0.06}\text{Ga}_{0.8}\text{As}/\text{GaAsP}$   
12 structures that allow the VECSEL 3 to be optically pumped  
13 at 808 nm, while generating an output in the range of 970  
14 - 995 nm.

15  
16 A first mirror within the cavity arrangement comprises an  
17  $\text{AlAs-GaAs}$  quarter-wave layered Bragg reflector 7 that  
18 exhibits a total reflectivity greater than 99.9% centred  
19 at 980 nm. A second mirror comprises a standard curved  
20 cavity mirror 8 mounted on a first piezoelectric crystal  
21 9, so allowing for fine adjustment of the length of the  
22 cavity. An output coupler 10, mounted on a second  
23 piezoelectric crystal 11, which allows for coarse  
24 adjustment of the length of the cavity, is then employed  
25 as the third cavity mirror. Between the curved cavity  
26 mirror 8 and the output coupler 10 is located a  
27 birefringent filter 12 employed to provide coarse  
28 frequency selection within the cavity.

29  
30 The wafer structure 5 is optically pumped by initially  
31 coupling the output of a pump laser source (not shown)  
32 into an optical fibre 13. Thereafter, the coupled pump

1 laser output is focussed via two input lens elements 14  
2 onto the wafer structure 5.

3

4 The stabilisation apparatus 4 can be seen to comprise a  
5 birefringent etalon 15 inserted with a slight angle  
6 between one of its axes and an intracavity electric field  
7 16 of the VECSEL 3. The birefringent etalon 15 is coated  
8 to act as a 25% reflecting etalon and so directs a  
9 reflected component 17 of the incident intracavity  
10 electric field 16 towards a beam steering mirror 18 that  
11 in turn reflects the field to a quarter waveplate ( $\lambda/4$   
12 waveplate) 19 and then onto an elliptical polarisation  
13 analyser. The first component of the polarisation  
14 analyser is a polarisation dependent beamsplitter 20 that  
15 divides the reflected electric field 17 into two  
16 components 17a and 17b each of which is then incident on  
17 a photodiode 21. An electrical circuit 22 is then  
18 employed to monitor the signals detected by the  
19 photodiode (as described in detail below).

20

21 The reflection coefficient  $A_r(\delta, R)$  for the reflected  
22 electric field 17 from the birefringent etalon 15 is  
23 given by the expression:

24

$$25 \quad A_r(\delta, R) = \sqrt{R} \frac{1 - \exp(i\delta)}{1 - R \exp(i\delta)} \quad (1)$$

26

27 where  $R$  is the intensity reflection coefficient and  
28  $\delta = 4\pi d n \cos(\theta) / \lambda$  is the phase retardation for a roundtrip  
29 of the light of wavelength  $\lambda$  in the birefringent etalon  
30 15 which has a thickness  $d$  and a refractive index  $n$ , and  
31 which is tilted at an angle  $\theta$  to the incident beam. This

1 reflection represents a periodic loss with a period (FSR)  
2 of  $c/(2nd\cos(\theta))$ .

3

4 Since the stabilisation apparatus employs a birefringent  
5 etalon 15 there are two refractive indices  $n_1$  and  $n_2$   
6 corresponding to the two axes of the material. Hence  
7 there are two different values  $\delta_1$  and  $\delta_2$  for the phase  
8 delay. In general this corresponds to different  
9 reflectivities for the two polarisations. By designing  
10 the birefringent etalon 15 so that the difference  $\delta_1 - \delta_2$   
11 is  $\pi$  modulo  $2\pi$ , one polarisation of the reflected  
12 electric field 17 experiences a reflection maximum when  
13 the other has a minimum. This is equivalent to the  
14 etalon acting as a  $\lambda/4$  waveplate for the incident  
15 electric field 16.

16

17 The ability to stabilise and tune the VECSEL 3 is  
18 achieved by inserting the birefringent etalon 15 in the  
19 laser cavity in such a way that the direction of  
20 polarisation forms a slight angle with one of the optic  
21 axes.

22

23 To initially demonstrate this effect we first consider  
24 the stabilisation apparatus 4 when deployed within an  
25 extra-cavity configuration, see Figure 3. This  
26 arrangement is adopted for simplicity of explanation  
27 since an intracavity arrangement is complicated by the  
28 laser jumping between successive cavity modes. The  
29 orientation of the polarisation components of the input  
30 laser are represented schematically within the insert of  
31 Figure 3. Specifically, the majority of the light  
32 (intensity of this component proportional to  $\alpha^2$ ) is  
33 polarised along this axis while a component proportional

1 to  $\beta^2$  has orthogonal polarisation ( $\alpha^2 + \beta^2 = 1$ ). Thus,  
 2 the incident electric field 16 can be written in its two  
 3 components along the axes of the birefringent etalon:

4

$$5 \quad E(t) = (\alpha E_0 \exp(i\omega t), \beta E_0 \exp(i\omega t)) \quad (2)$$

6 where  $E_0$  is the amplitude and  $\omega$  the frequency. The  
 7 reflected electric field is then given by the expression:

8

$$9 \quad E_r(t, \delta_1, \delta_2, R) = (\alpha E_0 A_r(\delta_1, R) \exp(i\omega t), \beta E_0 A_r(\delta_2, R) \exp(i\omega t)) \quad (3)$$

10

11 The operating frequency of the VECSEL 3, or the tilt  
 12 angle of the birefringent etalon 12, is chosen such that  
 13 the  $\alpha^2$  component is close to a reflection minimum. At  
 14 exact resonance the reflection of the component along  
 15 axis 1 vanishes and the reflected light is linearly  
 16 polarised 23 along axis 2. Away from exact resonance the  
 17 reflected electric field 17 is elliptically polarised  
 18 with opposite helicity for frequencies above 24 and below  
 19 resonance 25, as is expressed mathematically by Equation  
 20 3 above.

21

22 By inserting the  $\lambda/4$  waveplate 19, so that its axes are  
 23 aligned with those of the birefringent etalon 15, the  
 24 transmitted light now emerges linearly polarised. For  
 25 the case of exact resonance 23b the polarisation is  
 26 orientated along axis 2 and changes clockwise 24b and  
 27 counter-clockwise 25b, respectively, above and below  
 28 resonance. It should be noted that the relative rotation  
 29 of the linearly polarised transmitted light by the  $\lambda/4$   
 30 waveplate 19 would be reversed if the fast and slow axis  
 31 of the birefringent etalon 15 were reversed.

1  
 2 The incorporation of the polarising beamsplitter, which  
 3 is rotated 45° with respect to the axes of the  
 4 birefringent etalon 15, provides a means for analysing  
 5 the linear polarised fields 23b, 24b and 25b. For the  
 6 case of the on resonance polarised field 23b an equal  
 7 amount of light, 23c and 23d, is transmitted to both  
 8 photodiodes 21. However, for the cases where the  
 9 frequencies are above 24 and below resonance 25 the  
 10 amount of light transmitted to the photodiodes 21 is  
 11 asymmetric, the asymmetry being directly dependent on the  
 12 frequency shift, see components 24c 24d 25c and 25d,  
 13 respectively. This provides for the production of an  
 14 ideal signal for stabilising and tuning the VECSEL 3, as  
 15 is now described in detail.

16

17 The signal for stabilising the VECSEL 3 is a normalised  
 18 ratio signal 26 given by the following expression:

19

$$20 \quad S(\delta_1, \delta_2, R) = \frac{I_2(\delta_1, \delta_2, R) - I_1(\delta_1, \delta_2, R)}{I_2(\delta_1, \delta_2, R) + I_1(\delta_1, \delta_2, R)} = \frac{2\alpha\beta \operatorname{Im}[A_r(\delta_1, R)A_r^*(\delta_2, R)]}{\alpha^2|A_r(\delta_1, R)|^2 + \beta^2|A_r(\delta_2, R)|^2} \quad (4)$$

21

22 For demonstration purposes Figure 4 presents experimental  
 23 (dotted) and theoretical (solid) curves obtained for the  
 24 stabilisation apparatus 4 employed within the extra-  
 25 cavity configuration. In particular, the sum and  
 26 difference signals, 27 and 28 respectively, as well as  
 27 the ratio of the difference and sum signals 26 are  
 28 presented, as a function of laser input wavelength, over  
 29 three spectral ranges of the birefringent etalon 15. It

1 should be noted that these results were obtained by  
2 employing an uncoated birefringent etalon 15.

3

4 Further confirmation of this effect can be seen from  
5 Figure 5 which presents an experimental curve of  
6 birefringent etalon 15 tuning versus the normalised ratio  
7 signal 26, for the VECSEL 3 of Figure 2, where the  
8 stabilisation apparatus 4 is now employed intracavity.  
9 In this particular set up the birefringent etalon is  
10 coated so as to reflect 25% of the intracavity electric  
11 field 16. As can be seen, as the birefringent etalon is  
12 tilted the operating frequency of the VECSEL is tuned.  
13 The normalised ratio signal 26 takes the form of a  
14 sequence of continuous curves that pass through zero.  
15 The discontinuities correspond to mode jumping occurring  
16 in the operating frequency of the VECSEL 3.

17

18 The ratio signal 26, and in particular the positive  
19 gradient sections 29, are ideal for stabilising the  
20 birefringent etalon 15 to a minimum reflection point and  
21 hence for stabilising the VECSEL 3. This is achieved  
22 through the employment of a feedback loop (not shown) of  
23 the electrical circuit. In particular, the feedback loop  
24 acts to keep the birefringent etalon 15 at the zero  
25 crossing points of one of the positive gradient sections  
26 29. This is achieved by time integrating the ratio  
27 signal and thereafter transmitting a feedback signal,  
28 with the appropriate sign, so as to control the angle of  
29 rotation of the birefringent etalon 15, a technique that  
30 is known to those skilled in the art.

31



1 The electrical circuit 22 is also employed to provide  
2 signals to the first 9 and second piezo electric crystals  
3 11, thereby altering the cavity length and so altering  
4 the output frequency of the VECSEL 3. The feedback  
5 circuit is then employed, in conjunction with a reference  
6 signal forwarded from the first piezo electric crystal 9  
7 so as to allow the birefringent etalon 15 to track the  
8 controlled movement of the curved cavity mirror 8 and  
9 hence track the operating frequency of the VECSEL 3.  
10 This provides a means for continuously scanning the  
11 operating frequency of a single mode of the VECSEL 3 over  
12 a range of ~40 GHz.

13

14 The robust nature and flexibility of the above  
15 stabilisation apparatus 4 can be seen from the following  
16 considerations of the effect on the ratio signal 26 of  
17 various experimental parameters for the extra-cavity  
18 configuration employed in Figure 3. In the first  
19 instance, the calculated ratio signal 26 for a range of  
20 birefringent etalon 15 reflectivities, namely of 4%, 8%,  
21 12%, 16% and 20%, is shown in Figure 6. It is apparent  
22 that the effect of increasing the reflectivity from 4%  
23 (corresponding to uncoated quartz) to 20% only amounts to  
24 a slight increase in the slope of the positive gradient  
25 sections 29. Therefore, it will be apparent to those  
26 skilled in the art that the above described method and  
27 apparatus leaves the reflectivity of the birefringent  
28 etalon 15 as a free parameter that can be determined by  
29 the requirements of mode selection in a particular laser  
30 cavity.

31

32 As the method and apparatus is employed within a tuneable  
33 laser system it is also relevant to consider the effect

1 on the ratio signal 26 of a deviation from an exact  
2 quarter-wave retardation of the birefringent etalon 15.  
3 Generally speaking waveplates are only exact waveplates  
4 for a particular wavelength. The widest bandwidth for an  
5 etalon (i.e. the slowest variation of the phase  
6 retardation with respect to wavelength) is obtained with  
7 a true zero-order plate. Therefore, for the birefringent  
8 etalon 15 that is where the difference in optical  
9 thickness experienced by light polarised along the two  
10 optic axes is exactly a quarter of a wavelength. This  
11 generally corresponds to an extremely thin plate (tens of  
12 micron), that in practice is found to be too thin for  
13 practical use as an etalon. Within the VECSEL 3 a  
14 thickness of the order of 0.5 mm is required for the  
15 birefringent etalon 15 to perform its full function. As  
16 a result a higher-order plate is required to be used  
17 within the laser cavity, i.e. one where the optical  
18 thickness difference was  $q\lambda \pm \lambda/4$ , where  $q$  is an integer.  
19

20 For a quartz waveplate with an approximate thickness of  
21 0.3 mm the retardation is known to vary by less than  $\pm\lambda/8$   
22 when the laser wavelength is varied by  $\pm 20$  nm around the  
23 design wavelength. Figure 7 shows theoretical ratio  
24 signal for a variation of  $\pm\lambda/8$ . As can be seen the ratio  
25 signal 26 develops a slight asymmetry, but the zero-  
26 crossing remains at the correct point while the gradient  
27 at the zero-crossing remains unaffected. This clearly  
28 demonstrates that the technique is robust to realistic  
29 variations in retardation encountered in experimental  
30 realisations of the scheme and shows that the system may  
31 be readily incorporated for use within any continuous wave  
32 laser system that requires to operate single frequency  
33 e.g. Dye and Ti:Sapphire systems.

1

2 It will be appreciated by those skilled in the art that  
3 the stabilisation apparatus 4 will operate in a similar  
4 manner if the  $\lambda/4$  waveplate 19 is arranged so that its  
5 axes are aligned at  $45^\circ$  with those of the birefringent  
6 etalon 15. For the case of exact resonance 23 the  
7 polarisation of the emerging light is circularly  
8 polarised. However, as described above off resonance  
9 frequencies emerge linearly polarised, their plane of  
10 polarisation being rotated clockwise 24b and counter-  
11 clockwise 25b, respectively, above and below resonance.  
12 It should be again be noted that the relative rotation of  
13 the polarised transmitted light by the  $\lambda/4$  waveplate 19  
14 is reversed if the fast and slow axis of the birefringent  
15 etalon 15 are reversed.

16

17 The incorporation of the polarising beamsplitter again  
18 provides a means for analysing the resonant, circularly  
19 polarised field 23 and non resonant, linearly polarised  
20 fields 24b and 25b. The on resonance polarised field 23  
21 will again result in equal amount of light, 23c and 23d,  
22 being transmitted to both photodiodes 21. However, for  
23 the cases where the frequencies are above 24 and below  
24 resonance 25 the amount of light transmitted to the  
25 photodiodes 21 is again asymmetric, the asymmetry being  
26 directly dependent on the frequency shift, see components  
27 24c 24d 25c and 25d, respectively. Thus a signal  
28 suitable for stabilising and tuning the VECSEL 3 is again  
29 produced.

30

31 It will be appreciated by those skilled in the art that  
32 alternative relative angles between the  $\lambda/4$  waveplate 19

1 and the birefringent etalon 15 will still produce signals  
2 suitable for stabilising and tuning the VECSEL 3 however  
3 these will be of reduced efficiency to the arrangements  
4 described above.

5  
6 Aspects of the present invention exhibit a number of  
7 significant advantages over the stabilisation and laser  
8 tuning techniques employed in the prior art. In the  
9 first instance the present system employs fewer optical  
10 elements than those comprising passive stabilisation  
11 systems. This makes the systems simpler to align and  
12 maintain while reducing cost. Furthermore, the present  
13 system does not require the employment of an etalon  
14 modulation technique as used in known active  
15 stabilisation systems. This is of major benefit for the  
16 operation of the laser as it avoids the inherent losses  
17 and acoustic vibrations introduced to the cavity by the  
18 modulating etalon. A direct result of the removal of the  
19 effects of acoustic vibrations is that the control  
20 electronics can then be significantly simplified.

21  
22 The foregoing description of the invention has been  
23 presented for purposes of illustration and description  
24 and is not intended to be exhaustive or to limit the  
25 invention to the precise form disclosed. The described  
26 embodiments were chosen and described in order to best  
27 explain the principles of the invention and its practical  
28 application to thereby enable others skilled in the art  
29 to best utilise the invention in various embodiments and  
30 with various modifications as are suited to the  
31 particular use contemplated. Therefore, further  
32 modifications or improvements may be incorporated without

1 departing from the scope of the invention as defined by  
2 the appended claims.  
3